Requirements Development and Management on the Psyche Project

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***Abstract*— In January 2017, Psyche was one of two mission concepts selected by NASA for flight as part of the 14th Discovery mission competition. The project has been staffing up and maturing the spacecraft, instrument and mission system baseline designs on the path towards a 2022 launch. During much of 2018, the Project has been executing the lifecycle stage called Phase B, "Preliminary Design and Technology Completion," one key element of which is the development and management of requirements at various levels. In the case of the Psyche project, this process has been particularly unique for several reasons.**

The project utilizes a Solar Electric Propulsion (SEP) Chassis from Space Systems Loral (SSL), a high volume manufacturer of commercial geostationary (GEO) telecom spacecraft based on the 1300 satellite bus. While SSL has an extensive, well-vetted set of requirements based on their very successful Earth-orbiting product line, translating that heritage to a deep space science mission required special care. In addition to the differences associated with the deep space environment and longer communication times, new interfaces had to be incorporated. While a substantial portion of the Flight System consists of the SEP Chassis, there were several new interfaces within various subsystems between SSL components and those provided by JPL and other contractors. Managing these interfaces through requirements at a relatively higher level than normally seen on internal or external builds proved challenging. Finally, the Psyche spacecraft plans to host the flight terminal of the Deep Space Optical Communications (DSOC) technology demonstration, which is itself a separate project with its own requirements that must be flowed down and managed.

This paper will present an overview of the requirement development and management process for the Psyche project. It will discuss in detail the various challenges summarized above, the methods and decisions chosen to address them, and evaluate their overall effectiveness at this stage in the project.

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1. INTRODUCTION

In 2014, a two-step competition was initiated to select the next missions in NASA's Discovery planetary exploration program. This process culminated in January 2017, with the selection of two concepts for implementation, out of twenty-seven mission concepts initially submitted. One of these

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missions, *Psyche*, would use electric propulsion and a Mars gravity assist to rendezvous with and orbit the largest metal asteroid in the solar system. NASA's Discovery program has demonstrated the science benefits that may be attained through cost-capped, competitively awarded exploration missions beyond Earth orbit. In over twenty years since the launch of the first mission, NEAR Pathfinder, there have been a compelling list of successes, such as Mars Pathfinder, Lunar Prospector, Genesis, Deep Impact, Stardust, Kepler, GRAIL, MESSENGER and Dawn. [1]

For the last two years, the Psyche project has been supporting Phase B, which is denoted by development and management of requirements across multiple levels, from the project-level down to associated subsystems. This process has been particularly unique for Psyche for several notable aspects, from the first deep space mission of the 1300 bus, built by Space Systems Loral (SSL), to the interface definition between the Psyche spacecraft and the Deep Space Optical Communications (DSOC) technology demonstration, which is itself a separate project.

This paper provides an overview of the requirement development and management process for the Psyche project, highlighting the various methodologies that were implemented due to the unique aspects that make up the mission. Section 2 provides an overview of the Psyche project, the science objectives and mission implementation. Section 3 reviews the requirements development process, highlighting the requirement flowdown and implementation software approach. Section 4 outlines the key interfaces between the various partners the make up the flight system. Section 5 outlines the processes being used to manage the requirements, such as change requests and verification and validation processes.

2. BACKGROUND

The Science of Psyche

The Psyche mission is named for (16) Psyche*, a large (~279 x 232 x 189 km) asteroid orbiting the sun near the outer edge of the Main Asteroid Belt [3]. This body is unique in our solar system – scientists believe it is an exposed protoplanetary core, made almost entirely of metal, likely to have a landscape unlike any explored by NASA so far. The Psyche mission will increase our understanding of Psyche's present and past – and by doing so, provide insights into the formation of terrestrial planets in general.

It is believed that during the early years of our Solar System's formation, some planetesimals accreted enough mass to produce sufficient interior heat (through the decay of the short-lived ^{26}Al) for accumulated metal to melt and sink towards the center, resulting a differentiated body [13]. The leading hypothesis for how Psyche formed is that it began as one of these objects, and then endured a series of collisions that striped away its rocky exterior, leaving behind an exposed Ni-Fe core. Models of solar system formation suggest that between four and eight "hit and run" impacts are required to remove the outer layer of silicate rock from the metal core of such a planetesimal [14]. This rare occurrence that would explain why Psyche is unique in the solar system. If this mission's measurements indicate that *not* a core, it may instead be that the asteroid is composed of highly reduced, primordial, metal-rich material that formed closer to the Sun. The possibility has also been suggested that Psyche could be a rock-and-metal breccia, similar to the mesosiderite meteorites. [20]

The Psyche mission has three broad goals:
(1) Understand a previously unexplored building block of planet formation: iron cores;
(2) Look inside the terrestrial planets, including the Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen; and
(3) Explore a new type of world. For the first time, examine a world made not of rock or ice, but of metal.

The mission's science objectives are:
A. Determine whether Psyche is a core, or if it is unmelted primordial material.
B. Determine the relative ages of regions of Psyche's surface.
C. Determine whether small metal bodies incorporate the same light elements as expected in Earth's high-pressure core.
D. Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth's core.
E. Characterize Psyche's topography.

Table 1. Psyche Spacecraft Science Payload

Instrument	Flight Heritage	Key Measurements
Fluxgate Magnetometer [MAG] (x2)	Magnetospheric Multiscale Mission (MMS) and Insight	Magnetic field characterization
Gamma Ray and Neutron Spectrometer [GRNS]	MESSENGER	Elemental composition (i.e. Fe, Ni, Si, and K) Surface compo. heterogeneity
Multi-spectral Imager [PMI] (x2)	Curiosity Rover Mastcam	Surface geology, composition, and topographic
Gravity Science (X-band)	Multiple	Gravity field mapping

* The International Astronomical Union (IAU) designation is (16) Psyche. For clarity, we will use Psyche throughout this paper.

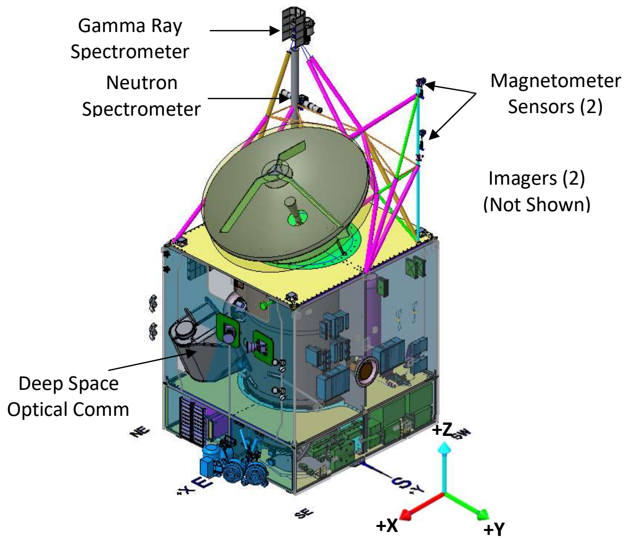

Figure 1. Psyche payload instrument accommodation

Science Instruments

The suite of instruments hosted on the spacecraft, as shown in **Table 1** and **Figure 1,** plus X-band gravity science directly address these science objectives. Data sets from multiple instruments can be combined to clarify and strengthen any resulting discoveries. A brief overview of each instrument is given here; for more details see ref [2] and [15].

Magnetometer

The magnetometers are provided by investigation lead Dr. Ben Weiss at MIT and development lead Dr. Chris Russell at UCLA. If a magnetic field is detected around Psyche this would confirm the hypothesis that Psyche a planetesimal core; no other theory would be consistent with the existence of a remanent magnetic field. Two identical fluxgate magnetometer sensors are spaced approximately 70 cm apart on a fixed two-meter boom, in a gradiometer configuration capable of rejecting the magnetic field from the spacecraft. The sensors can measure an ambient field ranging from 1nT to 10,000 nT in three axes. The resolution is ±0.1 pT and ±10 pT resolution in two (selectable) ranges of ±1,000 and ±100,000 nT, respectively.

Gamma Ray Neutron Spectrometer

The GRNS consists of gamma-ray and neutron sensors provided by instrument lead Dr. David Lawrence at the Applied Physics Laboratory. They measure the gamma rays and neutrons created when energetic Galactic Cosmic Ray (GCR) protons impact the Psyche's surface. These instruments will provide global – and in some instances, spatially-resolved – measurements of Iron, Nickel, Silicon, Potassium, Sulfur, Aluminum, Calcium, Thorium and Uranium concentrations on the asteroid.

The GRS has a high-purity germanium sensor surrounded by an anti-coincidence shield (ACS). The sensor is cooled via a pulse-tube cryocooler [16]. The ACS removes GCR-induced backgrounds in the gamma-ray spectra via a veto rejection.

Multispectral Imager

The Psyche Multispectral Imager (PMI) investigation is composed of two block-redundant imagers provided by instrument lead Dr. Jim Bell at Arizona State University (ASU) and Malin Space Science Systems (MSSS). Each camera images the surface of Psyche in eight visible and near IR spectral bands at moderate resolution. The imagers are nadir pointed during orbital operations and are used for optical navigation as well as science imaging.

Each camera is composed of a telescope (148 mm focal length, f/2.9 focal ratio), camera head (9-position filter wheel, and Focal Plane Array) and a Digital Electronics Assembly mounted separately on the spacecraft.

Gravity Science

The gravity science investigation, led by Dr. Maria Zuber at MIT, uses the spacecraft's X-band communications system to conduct radio science and map Psyche's gravity field. The recovered field accuracy depends on the geometric coverage of Psyche, the 2-way Doppler noise (due to media fluctuations and radio system noise) and the spacecraft's dynamic perturbations. It is expected that the gravity field will be determined to degree and order 12 in the closest planned orbit around Psyche.

Technology Demonstration

In addition to the science instruments, the Psyche project is also hosting a Deep Space Optical Communications (DSOC) technology demonstration that will test optical communications technology for high-rate data return from future deep space missions. The optical communication link will be exercised during the mission's cruise phase over Earth-probe distances ranging from 0.1 to over 2 astronomical units (AU).

DSOC operates as a separate project at JPL and is provided to Psyche as Government Furnished Equipment. The hardware hosted on the spacecraft is called the Flight Laser Transceiver and is composed of an Optical Platform Assembly, a 22cm diameter Laser Transmitter Assembly and a Stationary Electronics Module.

During operation, DSOC receives an uplink laser beacon transmitted from a Ground Laser Transmitter (GLT) located at Table Mountain in CA. The spacecraft points the flight terminal towards Earth, and DSOC then uses its built-in control system to search for and acquire the uplink beacon. Using the uplink beacon as a pointing reference and actively compensating for light time delays and spacecraft motion, DSOC uses its downlink laser to transmit data to a Ground Laser Receiver located at Palomar Observatory in CA.

Mission Design

To reach Psyche, the mission trajectory has been optimized to fit the on a "medium" class launch vehicle, as defined in the Discovery 2014 Announcement of Opportunity [20]. The amount of chemical propellant needed to orbit Psyche is prohibitively high, so the mission utilizes electric propulsion and a low thrust trajectory to travel to and operate around Psyche. The baseline trajectory (Fig. 2) uses an August 2022 launch and arrives at Psyche in 2026.

Since Psyche is a previously unvisited body, there is significant uncertainty in the knowledge of its gravity field. The planned science orbits must be robust to current measurement uncertainties in shape, density variations, pole orientation and rotation rate. To that end, the orbit design (Fig. 3) consists of a series of progressively lower circular orbits; a recursive technique successfully demonstrated by Dawn [17] [18] [19].

The Psyche Spacecraft

The spacecraft's prime mission is to deliver the science payload to Psyche and provide the required observing conditions and data management during the 21 month science campaign at the asteroid. It must also operate DSOC at various distances from Earth during the cruise to Psyche.

To accomplish this goal within Discovery-class constrains, ASU and JPL have partnered with SSL – a high volume manufacturer of commercial high-power geosynchronous communications satellites. SSL's development experience is limited to Earth orbiting spacecraft, and SSL and JPL have never before worked on a project of this magnitude. For Psyche, a new partnership model was developed to take advantage both SSL and JPL's decades of spacecraft development expertise. SSL was tapped to develop the Solar Electric Propulsion (SEP) Chassis. This includes the structure, power distribution and storage, propulsion system, solar arrays, thermal control, attitude control sensors and actuators. To develop the Chassis, SSL will draw on the extensive heritage and high volume efficiencies of its current commercial product line, which includes the 1300 satellite bus. JPL, leaning on heritage from deep space missions like the Curiosity Mars rover and Soil Moisture Active Passive Earth orbiter, is responsible for the development of the command and data handling (C&DH) hardware, telecommunications and all spacecraft Flight Software (FSW) (including guidance and navigation, avionics algorithms and fault protection). The entire vehicle, including instruments, will be integrated and tested at JPL prior to ship to launch base. Figure 4 illustrates the delineation of duties between SSL, JPL and the instrument providers.

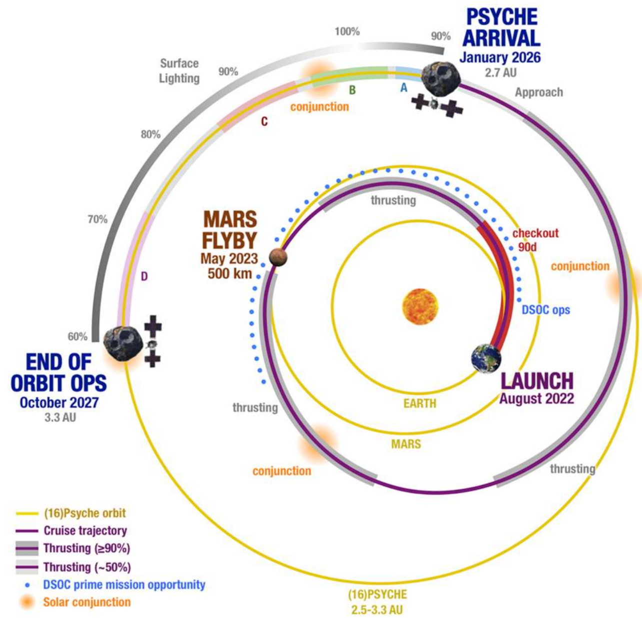

Figure 2. Psyche Cruise Trajectory

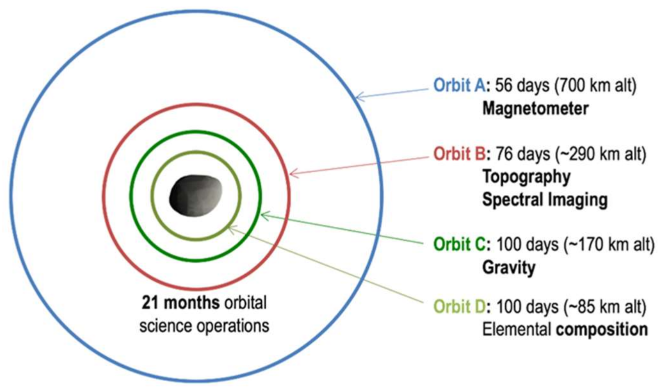

Figure 3. The planned Psyche Science Phase consists of four orbits at decreasing orbital altitudes

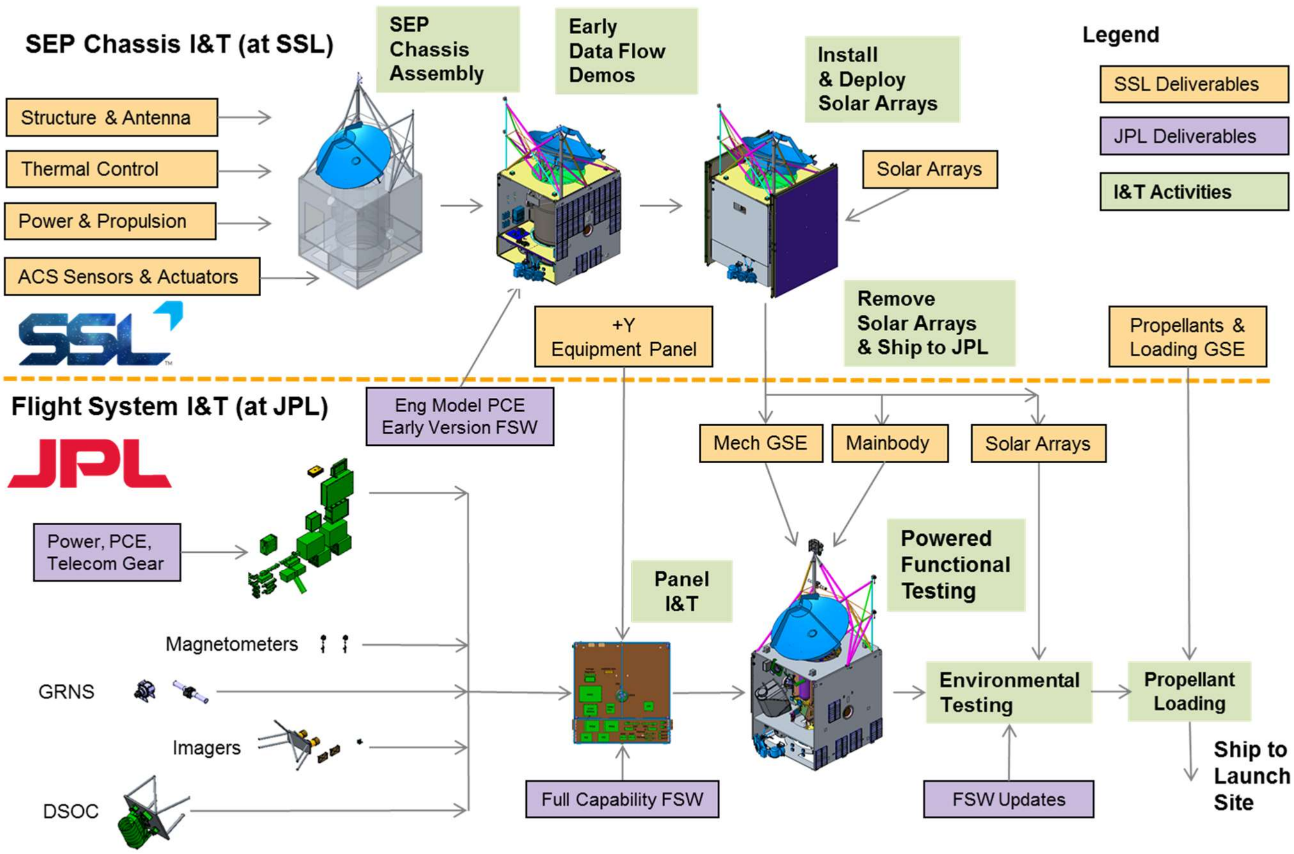

Figure 4. JPL and SSL integrated Flight System development for a low cost-risk Discovery-class SEP spacecraft

3. Requirements Development

Requirements Structure

The requirements structure and hierarchy follows in general the structure of the project. The Psyche Project System is composed of three parts: the Flight System, the Launch System and the Mission System. Although the Launch System is important, typically the Flight and Mission Systems require the bulk of the effort in requirements development and management, and those will be the focus of this paper.

The Flight System includes the Spacecraft System and the Payload System. The Spacecraft System is further decomposed into the SEP Chassis (provided by SSL) and the other subsystems (provided by JPL). The Payload System includes the science payload (Magnetometer, Gamma Ray Neutron Spectrometer [GRNS], and Imager) and the technology demonstration payload Deep Space Optical Communications (DSOC).

The Mission System has a large variety of constituent parts. The first is the Mission Design and Navigation System, that which directs the Flight System to its destination and into the desired science orbits about the asteroid. Closely coupled with this are the Mission Operations System which plans and executes spacecraft and payload operations, and the Ground Data System which provides uplink/downlink capability, command processing, data storage, etc. Finally, the Mission System includes the Science Data Center, located at Arizona State University, which stores and distributes the science data.

The project structure, as stated earlier, is reflected in the requirements hierarchy that is shown in Figure 5. Project System requirements live at Level 2 and directly respond to the Program Level Requirements at Level 1, which are approved by NASA Headquarters. JPL is responsible for approving the Level 2 and all of the Level 3 requirements.

Unique to the Psyche project is the definition of the SEP Chassis requirements at Level 3.5. These requirements are a combination of flowdowns from Level 3 and typical SSL spacecraft requirements as described in later sections. These Level 3.5 requirements are approved jointly by JPL and SSL, and serve as parents for the JPL-reviewed and SSL-approved Level 4 SSL subsystem requirements. The Level 4 requirements for the JPL-provided subsystems flow directly from the Level 3 Flight System requirements.

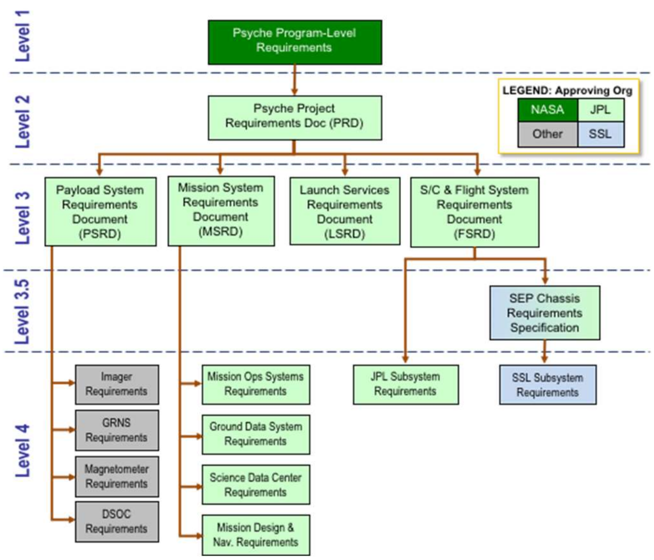

Figure 5. Psyche Project Requirements Hierarchy

Level 4 payload requirements are approved by the individual providing organizations for each instrument. Requirements for the DSOC technology demonstration instrument in this regard are treated like all of the other payload instruments.

Not shown in Figure 5 are the environmental requirements which live at Level 3 and flow down independently from Level 2 to Level 4, applying to all subsystems. Also not shown are the payload accommodation and compatibility requirements which cross-link the Level 3 Flight System and Level 3 Payload requirements through the payload Interface Requirements and Control Document (IRCD).

Requirements Implementation Application

During the early phases of mission concept development and the Step 2 proposal process, requirements were developed and managed on Excel spreadsheets. The Psyche requirements spreadsheet followed a basic table structure, where each row was a requirement, and column was a field or attribute describing the requirement. The Psyche requirements spreadsheet contained the following columns: as ID, primary text, and rationale. The requirements spreadsheets were easily exchanged between the members of a smaller proposal development team, where only a handful of team members were writing requirements. When the Psyche project was selected for implementation and proceeded into its next phase, the development of requirements on spreadsheets became harder to configuration manage, as the project team grew in size and needed a tool that would enable the collaboration and development of requirements across dozens of requirements writers and owners. To accomplish this, the Psyche project had to transition from working on spreadsheets into DOORS Next Generation (DNG).

DNG is a browser-based application for development and management of requirements. DNG allows for collaboration and review of requirements, enables traceability across the requirement hierarchy, and planning of verification activities. In DNG, various artifacts can be created and stored. Examples of artifacts include requirements artifact, verification artifact, acronym artifact, and documentation artifact. The most used artifact on Psyche, is the requirement artifact. Each artifact contains various attributes, or fields, similar to columns in a table. For example, a requirement artifact contains many attributes, including short text name, primary text, rationale, owner, verification method, and verification approach. DNG has powerful features, including the ability to manage requirements development through workflow states. The Psyche project looked at the requirements workflow used on other JPL projects and has customized the workflow states of its requirements artifacts to encompass the entire process from the beginning of requirements development through the completion of requirements verification. The workflow for Psyche are shown in Figure 6.

As a requirement artifact is developed, on Psyche, it moves through states, from draft to preliminary to baselined. When a requirement is “baselined” certain attributes or fields are no longer editable without a formal engineering change request. In addition to the “[REQ] Baselined” state, a requirement can move further into V&V planning states.

A main feature of DNG is that the tool allows for the easy import of requirements from spreadsheets and documents, which allowed Psyche to efficiently import the large number of requirements it accumulated during the Step 2 process. After importing of the requirements from their spreadsheets, the Psyche team began the task of linking parent and children requirements, which is not easily implementable in a spreadsheet, but easily achievable in DNG. DNG allows for the linking of requirements from various levels, which enables traceability and visualization of the requirements hierarchy.

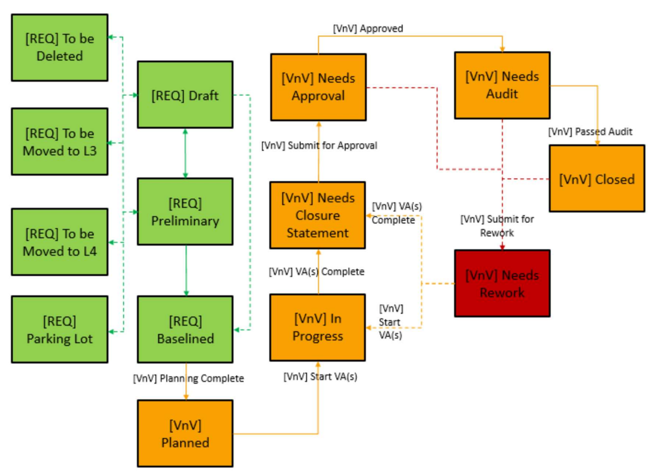

Figure 6. Psyche requirements workflow states

Once Step 2 requirements were in DNG, the Psyche team desired customized requirement attributes and custom linkages. As DNG is a fairly new tool to our institution and

Psyche is one of the first projects to use DNG, there was no standard set of attributes or workflows to follow. The Psyche project worked with the few other DNG projects to adapt their flows and attributes, but the needs of each project are different and thus were Psyche's customizations and adaptations of DNG. While all JPL projects have primary text and unique ID as attributes for their requirements artifacts, the Psyche project has adapted in different ways and added different and project-specific custom attributes. Some custom attributes that worked well for the early phases of the project became less useful as the requirement database matured. For example, the attribute 'Section Title' was used for all L2 requirements to facilitate organization into the L2 Project Requirements Document (PRD) Module. However, as lower level requirements were developed, the owning teams did not use the 'Section Header' attribute to organize their requirements into modules, and instead leveraged 'Tags' and Folders to organize their requirements, making the 'Section Title' attribute unused for many requirements.

4. KEY INTERFACES

Requirements Interface with SSL

Developing the requirements for the Psyche SEP Chassis would typically start with the Level 1 science requirements and the mission's design, which would then be used to derive a unique set of lower level performance requirements for the spacecraft and its SEP system. The procurement of a spacecraft designed to such a customized set of requirements is in keeping with the cost plus contracting approach commonly used by NASA. In a deliberate break with this approach, the Psyche leadership team made the calculated decision to procure an existing commercial SEP design from SSL using a Firm Fixed Price (FFP) contract, to requirements based primarily on SSL's existing performance capabilities. To accomplish this the requirements for the Psyche Spacecraft were developed using a collaborative process is which the requirements flowed both up and down between JPL and SSL interactively to balance performance against cost and risk.

The integrated JPL/SSL Systems Engineering team's solution to the challenge of adapting SSL's high power bus electronics and SPT- 140 electric propulsion engine system is illustrative of the interactive capabilities based approach used for Psyche. The modification to the requirements for each element of the SEP system were strictly limited to only to those resulting in straight forward engineering changes. No new technologies, materials, processes or qualifications were permitted. The key to arriving at the solution for Psyche under this constraint was to connect SSL's existing battery discharges directly to the solar arrays to boost raw incoming solar power with varying voltage to power the constant voltage Electric Propulsion system. The team's patent pending solution minimizes electrical loses at the missions critical power point at the orbit of Psyche were the available sun light has only 10% of the intensity at earth. All the required design changes are well within the design flexibility of SSL's standard commercial practices ensuring that SSL is able to provide the SEP Chassis to NASA under FAR 12 as a Commercial Item.

Formally documenting the agreed to design requirements for the SEP Chassis was accomplished by adapting SSL's existing commercial contract performance specification. For the most part this consisted of deleting the complex RF payload requirements of a communications satellite while emphasizing the optimized propulsive enhancements described above. The second key step was to explicitly identify in SSL's FFP contract a complete list of all the existing hardware required by SSL part number.

Fundamental to enabling this approach was the decision to keep SSL's SEP Chassis as simple as possible by having all the mission flight software and autonomous deep space fault recovery be developed entirely by JPL and implemented on JPL's hardware. The interface between SSL's Data Handling System (DHS) and JPL's was reduced to two clearly defined interfaces. One for SSL's MBus implementation and one for a 1553 standard.

Through Phase B, JPL and SSL have continued to refine the requirements for the SEP Chassis in accordance with these same guiding principles. Both organizations implement the detailed requirement validation and verification process through formal implementation in DOORS. The SEP Chassis specification is considered a Level 3.5 document which functions as the requirements interface between the JPL's Level 3 Flight System specification and SSL's Level 4 subsystem specifications. JPL manages the requirements flow down from the FS to the SEP Chassis specification while SSL manages the flow down from the SEP Chassis specification to the SSL subsystems. Both JPL and SSL work jointly to refine the Level 3.5 SEP Chassis specification, which documents SSL's carefully constructed contractual performance requirements.

Requirements Interface with DSOC

Psyche hosts the Deep Space Optical Communications (DSOC) technology demonstration payload. While physically hosted on the Psyche spacecraft, DSOC is an independent project with different sponsors and risk classification than Psyche. Fortuitously, both Psyche and DSOC use DNG to manage project requirements, enabling the two projects to easily establish parent-child linkages within DNG across the separate project databases. Psyche includes an attribute to indicate which of its requirements are flowed to DSOC.

DNG views are used to display requirements for which DSOC is listed as a child, and the DSOC project systems engineer dispositions each to accept, reject, or mark them as not applicable. DSOC responses are then reviewed by the requirement owner and implementer. When further clarification is needed, the comment feature in DNG is used to capture and resolve concerns to enable disposition. Accepted requirements are reflected in the Psyche-DSOC Interface Requirements Control Document (IRCD).

Requirements Interface with Payload Instruments

Psyche Payload requirements are considered those requirements that live at Level 3 within the project requirement hierarchy and are owned by the Payload System. These requirements originate from several sources and/or needs. The first source is a flow down of science requirements from L2 that need interpretation and/or decomposition prior to flowing directly to an instrument at L4. Many of the science requirements at L2 do not require any further interpretation or decomposition prior to being flowed to an instrument and thus are not represented at L3 but flow directly from L2 Project to L4 Instruments, as shown in Figure 7. This is in large part due to a concerted effort during the Psyche Project Phase A effort (related to Discovery Step 2 proposal preparation) of developing a detailed science traceability matrix.

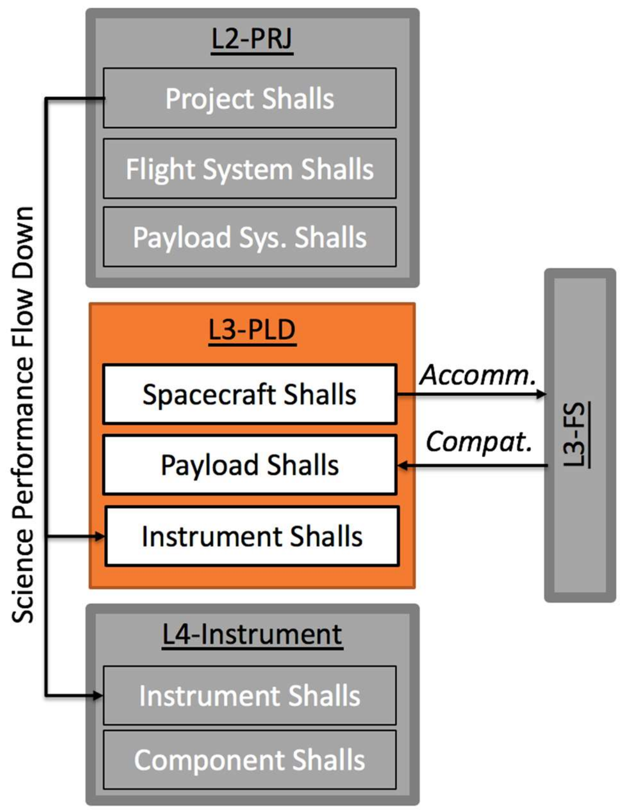

Figure 7. Payload Requirements Connect Instruments to the Spacecraft and the Project.

The second source of Payload requirements comes from any combined or related utilization of instruments to meet science goals. For the Psyche mission, the operation of the instruments is fully decoupled. No single science investigation nor technology demonstration must operate with another to be successful. However, there are a couple of requirements in the Payload set that require the use of multiple instruments in order to achieve.

A third source of Payload requirements are accommodation needs of the instruments, referred to as accommodation requirements. These requirements form the largest category within the L3 Payload set and represent the services and interfaces that the instruments must have in order to be successful within the Psyche mission. These requirements are typically levied on the Spacecraft and Mission System. They are owned by the Payload System with inputs from each instrument to make clear what is needed for environments, command and data handling, fault protection and operations.

The fourth and final set of Payload requirements are formed by those "compatibility" requirements levied on the Payload System by the Flight System or Spacecraft. The majority of these requirements are in face owned by the Flight System and thus are of L3-FS type, however some are either system allocation requirements, or require decomposition or interpretation before flowing to instruments for implementation.

The Payload System requirement set was developed in an iterative manner that included representation from the Project System Engineering team, Spacecraft and Instruments. Starting points came from the Psyche proposal effort, heritage programs at JPL and heritage versions of the science instruments. All of the requirements were reviewed in both tabletop and formal review settings, and are configuration controlled in DNG.

Instrument requirements reside at Level 4 in the project hierarchy. The instrument requirements are configuration controlled and managed at each instrument provider's institution, however the baselined and approved set of L4s are represented in the Psyche DNG database at JPL for the purposed of linking to parent requirements and understanding traceability. This is key for understanding the impacts of any changes or waivers to requirements.

Instrument requirements are developed by each instrument team and respond to Psyche L2-PRJ, L3-PLD, and L3-FS requirements as necessary. Instrument requirements also contain many self-derived requirements that are key to meeting the science performance demanded by the mission. These requirements are reviewed ahead of each instrument Preliminary Design Review (PDR) and baselined at the conclusion of that review.

5. Requirements Management

Managing Change Requests

When a requirement change is identified, a Change Request (CR) is routed through the Engineering Change Request (ECR) process, shown in Figure 8. The requestor fills out the CR form with the proposed requirement attribute changes, and presents the request at the Change Control Board (CCB) for approval. Once a CR is approved, the requirement is unlocked in DNG, the changes are implemented, and the requirement is re-locked in a baselined state. A CR artifact which hyperlinks to the official CR record is created in DNG and linked to the modified requirements for traceability. Periodic releases of the requirements are made by exporting Requirement Modules from DNG in a document format, and submitting to the Psyche's engineering product data management system.

Prior to CDR, the requirement attributes that are under configuration control, requiring a CR to modify, are the ID, Name and Primary Text. After CDR, the Verification Method, Verification Approach, Child Systems and Responsible Organization attributes are additionally under configuration control. Changes to rationale, links, owner, etc. will be recorded in DNG, and the owner will be informed of changes, but these changes do not require a CR at any point in the life cycle.

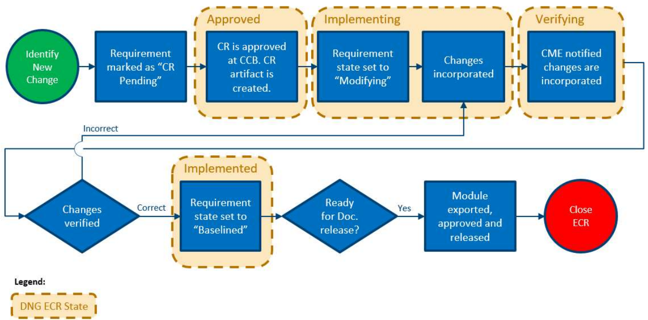

Figure 8. Requirement ECR Implementation Workflow in DNG

A process for enabling efficient change requests for requirements that were not officially released yet, but were set to a "Baselined" workflow state, was developed for Psyche. ECR-lite was a DNG artifact we created that allowed team members to propose their changes and not have to go to an official Engineering Change Board meeting. Changes listed in the ECR-lite artifact were reviewed by the impacted team members and approved by the team lead.

Reviewing Requirements

The L2 requirements were derived from either heritage projects such as Dawn, Juno, and SMAP or JPL institutional checklist as shown in Figure 9. The initial ~280 Draft requirements went through iterative reviews by SMEs in each area. These reviews reduced the overall count to about 140~150 Preliminary requirements by deletion of duplication and demotion to L3 requirements. During this process, the rationale behind the text of each requirement was captured and V&V approach specified. Additionally, each requirement was linked to L3 level, e.g., Flight System (FS), Payload (PLD), and Mission System (MS), with a Child requirement in DNG. Similar review process was iterated to achieve the released Baseline L2 requirements and under ECR configuration control, starting in April 2018.

Initial L3 requirements were derived from L2 requirements by the SMEs from different disciplines in the FSE team. Those requirements are grouped by the discipline area in DNG and owned by the FSE team member in each particular area. Note that in order to allow sufficient lead time for SSL to develop and procure spacecraft hardware, L3.5 SEP requirements are developed and reviewed iteratively, through a process with some slight variation.

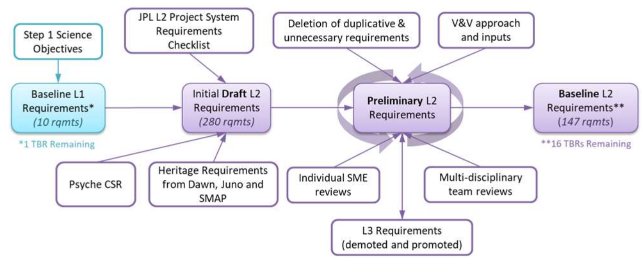

Figure 9. L2 Requirement Development and Review Process

During the L3 requirement development and review process, two notable trends arose:

1. Ownership vs. implementation

   Early in the L3 requirements development process, it was important to delineate clear owner vs. implementer of all given requirements. For example, a particular instrument's pointing accuracy requirement is owned and managed by the Payload System, but responsibility for implementation resides with the Flight System. The rationale is that PLD is the system driving this requirement and FS is the system being imposed to implement this requirement. In order to distinguish the ownership, e.g., L3-FS, L3-PLD, L3-MS, etc., from implementation, a custom attribute "Implementing Systems" was created within DNG for Requirement artifact types. This attribute allows a user to select multiple systems as implementer for a given requirement.

2. Need vs. owner

   Scenarios also existed in which the development of a requirement was shepherded by a group that was responsible for its need, but upon completion, moved to another group as owner. For example, the solar array pointing requirements were needed by L3-EPS area based on power budget. However, once the requirements were developed and reviewed, the ownership was changed to the Guidance, Navigation and Control (GNC) group for management and implementation.

Once the pertinent Flight System Engineer (FSE) has developed the L3 requirements against their L2 parents, by either revising L3 requirements accordingly or removing duplications, each L3 requirement set (e.g., L3-GNC for GNC algorithms) is designated a formal group review in DNG by the related parties in the team in order to promote status from Draft to Preliminary, then Baseline. During this process, the V&V method & approach, parent/child requirements links were developed and examined as well, similar to the L2 process discussed earlier. As of this writing, over 400 L3 requirements were developed for the bus components of the Flight System.

Because of Psyche project's aggressive schedule consideration during the first six months after L3 requirements baselined, it was necessary to develop a configuration that provided configuration control for Flight System and Payload Management, yet allowed flexibility in changing requirements still in flux. A new process called "ECR-Lite" was created. Within this process, the requirement initiator only needs to create a new artifact in DNG with a custom artifact type "ECR-Lite", with the requested changes filled in. This ECR-Lite change would go through group review, along with major stakeholders, in order to obtain concurrence from affected areas. After making changes per affected feedback from the stakeholders, the requirement would then be reviewed by Flight System management and, upon approval, modified accordingly. This process avoided being restricted to CCB meetings that were held weekly and required the in-person presence of all major stakeholders in order to approve a change.

In the early stages of L3 development, the flowdown of each L3 requirement to its L4 subsystem level (or, in the case of the SEP Chassis, L3.5-SEPC level) was designated an attribute called "Implementing System", e.g., "Implementing System: GNC", "Implementing System: Power", to flow down to either single or multiple subsystems. Later on, when the FS Implementer, PLD Implementer, etc. types were invented, the "Implementing System" was deemed too confusing to distinguish between L3 and L4 subsystem levels. In addition, at L4 level, which is to implement specific design, there is no need to differentiate owner vs. implementer. As a result, the Psyche team chose to develop another custom attribute, "Child Disposition". attribute is used instead.

While each subsystem developed its own L4 requirements following L3 requirements with corresponding "Child System" attribute, subsystem system engineers need to review and decide whether L3 requirements make sense or not. This is an iterative process between L3 FSE and L4 subsystem system engineers. In order to track the flow down status, a new attribute "Child Disposition" for L3 requirements was invented. In this way, one L3 requirement can be flown down to multiple L4 subsystems. After reviewing one particular L3 requirement, subsystem system engineer needs to choose either accept, reject, or mark not applicable (N/A) in the "Child Disposition" field. If the requirement is rejected, both L3 and L4 system engineers need to work together to refine the L3 requirement in order for this requirement to become acceptable.

To track the progress of L3 requirement flowdown to L3.5 and L4 level, the status was actively tracked and updated as part of each week's FSET meeting. Before the "Child Disposition" attribute was invented, it was difficult to track how many L3 requirements were actually accepted by subsystems, as one L3 requirement can be flown down to multiple subsystems and one subsystem can accept this requirement, while the other subsystem rejects it. DNG has a 'Review' function that can be helpful in disseminating new requirements through a large group of stakeholders. However, the review process was found to be less helpful when the requirements development was in an iterative state. Table 2 illustrates a list of child disposition subsystems for both payload and flight system implementer requirements.

L3.5 SEP requirement review is a unique case for Psyche project because SSL is an external partner responsible for most the spacecraft hardware, which has its own requirement process. In order to meet lead time in the contract, JPL has to provide requirements at very early stage. Therefore, the review process started with SSL provided their customized requirements for Psyche derived from their standard GEO bus requirements. After SMEs at JPL reviewed and added JPL specific requirements from either heritage projects or institutional checklist, the requirements were sent back to SSL for review. This was an iterative process.

When SSL found requirements they cannot meet, negotiation or refinement on the requirements were worked between the SSL and JPL engineers. Additional effort was taken to ensure requirements flowed down to SSL were worded such that they only applied to SSL inputs to the project, rather than inputs which contained components from other contractors. For example, a solar array pointing accuracy requirement, if written vaguely, could be constructed as a combination of SADA accuracy and GNC algorithm. After careful consideration, the requirement was reworded such that only the SADA accuracy portion was imposed on SSL and became a L3.5 requirement.

Table 2. List of 'Child Disposition' subsystems

Payload Implementer Requirements	Flight System Implementer Requirements
Magnetometer	Avionics
Gamma Ray and Neutron Spectrometer	GNC Algorithms
Multispectral Imager	JPL Power Components
Deep Space Optical Communications	JPL Telecommunications Components
DSOC Accommodation Kit (DAK)	Payload Subsystem
	SEP Chassis
	DSOC Accommodation Kit (DAK)

Verification and Validation

One of the important aspects of developing requirements is determining what work is needed to close them. That is to say, once the project has written a requirement it then needs to ensure that that requirement is implemented in the design and then to verify that the flight hardware meets those same requirements. Given that Psyche is still in the early stages of development there are several methods that can be used to help ensure that the requirements that the team is capturing now can be verified later during phase D.

First, it is necessary to ensure that the requirements are reviewed for verifiability. Necessary attributes of this include that the requirements are written in plain English, use only definitive terms, and clearly define the system/subsystem that the requirement is placed on. This will ensure that while the team is hurriedly trying to prepare a final set of requirements they will not end up with an unverifiable requirement, once the system has been built. In addition, one must ensure that each requirement has a rationale that describes the reason the requirement was developed. Linking to parents and children are necessary, but usually insufficient by itself to achieve this task.

Also, one must capture both a method (test, analysis, inspection, or demonstration) and an approach (one short sentence describing the general idea for how the requirement will be verified), as the requirement is being written down, this way when the team is looking back at a requirement that was written multiple years earlier, they have an idea of how they initially envisioned for how to verify the requirement. Employing these methods will not necessarily ensure that the verification process will go smoothly, but can potentially mitigate issues later in the program schedule.

6. Conclusion

The Psyche mission is enabled by a unique architecture, combining SSL's experience with high power spacecraft and electric propulsion, and JPL's experience building highly autonomous spacecraft for deep space missions. The architecture is built around the concept of a SEP Chassis, derived from SSL's GEO product line, combined with a heritage C&DH, telecommunications, and FSW to form the Psyche spacecraft bus. The use of SSL's SEP Chassis provides the benefits of flight heritage, a steady product line and low cost-risk. The use of JPL's heritage C&DH and FSW mitigates risk associated with deep space, autonomous operations and fault protection.

This architecture provides high heritage while leveraging the strengths of its partner organizations, but also introduces substantial issues with regards to the development and management of requirements, from the highest level down to the various subsystems that make up the project. Since its selection for implementation as part of NASA's Discovery exploration program, there has been significant efforts over the last two years with regards to the requirements development and management. Through the effort of the engineers that make up the Psyche team across multiple partners, methods have been implemented, as described in this paper, to alleviate these concerns without diminishing the strengths of the project architecture.

Acknowledgements

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and at Space Systems Loral under a contract with the National Aeronautics and Space Administration. The authors would like to thank G. Mark Brown of the Jet Propulsion Laboratory, California Institute of Technology, for their assistance in the development of this paper. The authors would also like to thank NASA's Planetary Science Division, NASA's Discovery Program Office, and JPL's Solar System Exploration Program Office for their support of this work.

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